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# The Athena Optics

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## ABSTRACT

The Advanced Telescope for High ENergy Astrophysics (Athena) was selected in 2014 as the second large class mission (L2) of the ESA Cosmic Vision Science Programme within the Directorate of Science and Robotic Exploration. The mission development is proceeding via the implementation of the system studies and in parallel a comprehensive series of technology preparation activities. [1-3].

The core enabling technology for the high performance mirror is the Silicon Pore Optics (SPO), a modular X-ray optics technology, which utilises processes and equipment developed for the semiconductor industry [4-31].

This paper provides an overview of the programmatic background, the status of SPO technology and give an outline of the development roadmap and activities undertaken and planned by ESA.

**Keywords:** X-ray optics, X-ray astronomy, Athena, Silicon Pore Optics, X-ray telescopes, X-ray testing, Technology preparation

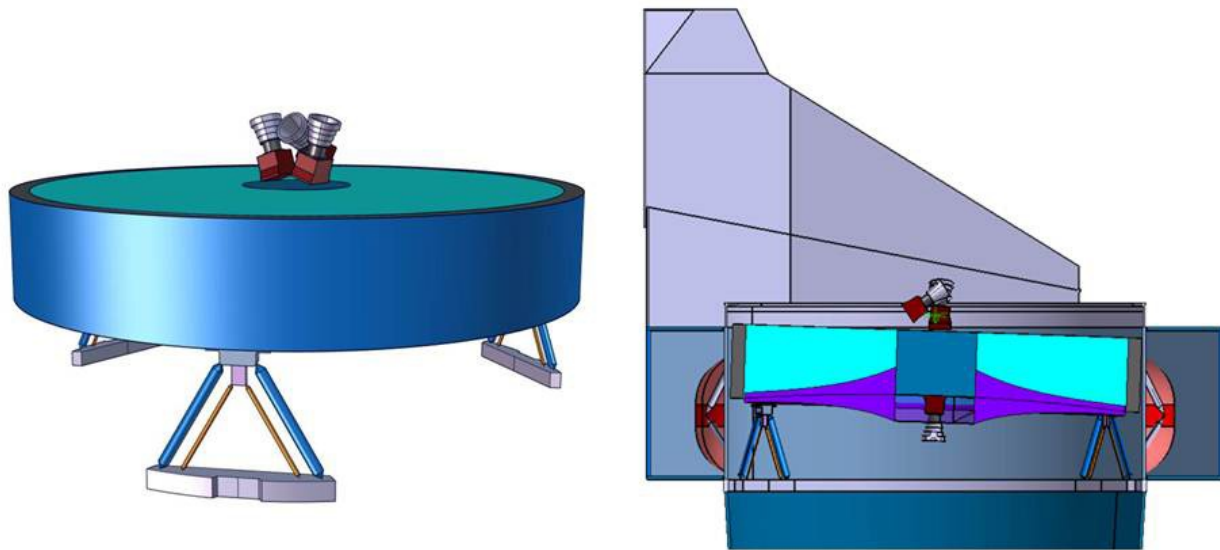
## 1. REQUIREMENTS AND ACOMMODATION

Athena is an ambitious mission aiming at the study of the hot and energetic Universe using a powerful X-ray telescope. In order to provide the required sensitivity to observe faraway sources to study the gas in clusters and groups of galaxies, and to investigate the properties of distant and obscured black holes, the mission proposal asks for a large effective area ( $\sim 2 \text{ m}^2$  at 1 keV) and a good angular resolution (5 arc seconds Half-Energy-Width (HEW) on-axis). . Two detector instruments are proposed to share the single focus at 12 meter distance from the optics: an X-ray Integral Field Unit (X-IFU) high resolution cryogenic Transition Edge Sensor (TES) based spectrometer, and a Wide Field Imager (WFI) utilising a DEpleted P-channel Field Effect Transistor (DEPFET) array.

In a competitive process, Athena was selected as the second large class mission (L2) in the ESA Science programme. An internal system level study was conducted in the ESA Concurrent Design Facility (CDF) in 2014, and recently two parallel industrial system level studies have been kicked-off. In addition to the technical requirements, also programmatic constraints are to be considered: a launch in 2028, and a cost cap to ESA of about 1 B€. The instrument costs are not included in this sum but rather are covered by the ESA member states represented within the instrument consortia. In

parallel the required technologies are being developed, in order to achieve a Technology Readiness level (TRL) of 5/6 according to the ISO scale [32] before the mission adoption, which is expected in 2020.

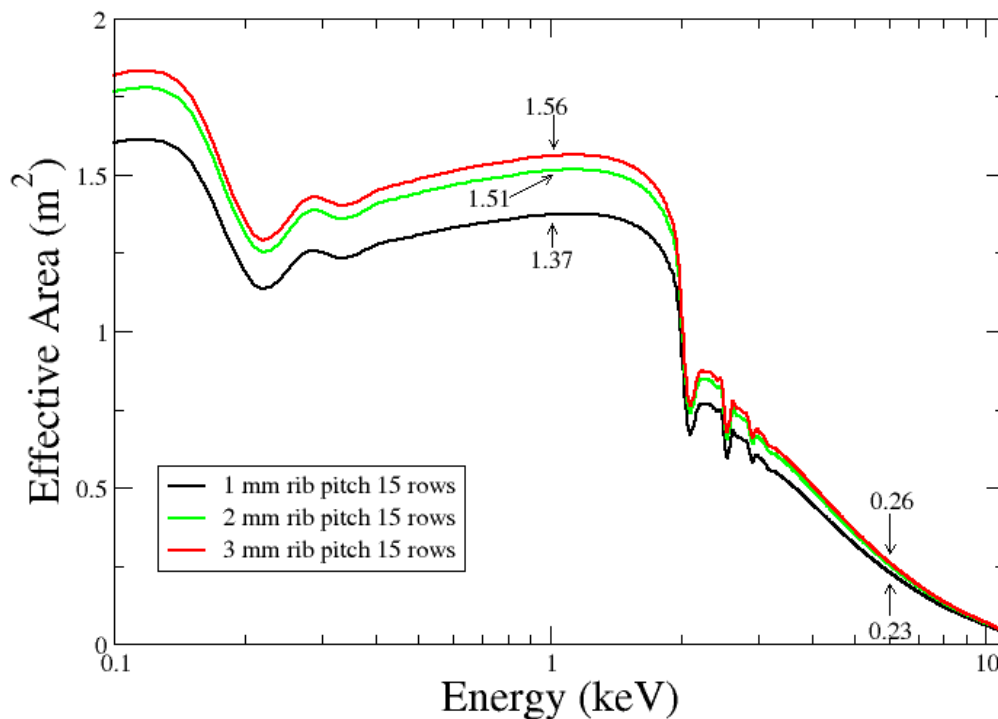
Silicon Pore Optics (SPO) is the chosen X-ray optics technology for Athena, and the CDF derived configuration foresees a single optical bench, populated by 678 SPO mirror modules in 15 rows, with an outer diameter of  $\sim 2.4$  meters, fitting inside the 2624 mm launcher interface flange. As shown in figure 1, the telescope optics is supported by a hexapod, which allows the optics to be tilted, thereby selecting the active focal plane instrument. An additional benefit of this configuration is the ability to correct for post launch misalignment between mirror and focal plane. Star trackers are mounted in the centre of the telescope optics structure, ensuring a stiff connection with minimal drifts. A sun-shield protects the optics and provides the necessary thermal environment with a large allowable range for the solar aspect angle.



**Figure 1:** The Athena telescope optics consists of a mirror structure (optical bench) populated by Silicon Pore Optics (SPO) mirror modules. Left: in the baseline configuration defined in the Concurrent Design Facility (CDF) of ESA, the optical bench is supported by a hexapod system, which allows to tilt the optics to reach either of the two focal detector instruments of Athena. With its many degrees of freedom, the hexapod system also permits the focusing of the telescope and lateral alignment of the focal position. The star trackers are mounted onto the same optical bench, ensuring high rigidity. Right: in the cross section the profile of the optics is visible, with the mirrors arranged in the Wolter-Schwarzschild configuration to improve the off-axis performance. Also shown is the sun-shield, and, opposite to the star-trackers, the optical alignment metrology system. The focal length of the telescope is 12 m.

The CDF baseline provides an on-axis effective area of about  $1.5 \text{ m}^2$  at 1 keV, see figure 2. The optics coating is assumed to be Iridium with an overcoat of boron carbide.

Each mirror module contains 70 mirror plate pairs, grouped into four stacks of 35 plates, two hyperbolic stacks and two parabolic stacks. Adjacent mirror plates are separated by ribs, and in figure 2 the dependence of the effective area on the chosen rib-to-rib spacing is shown.



**Figure 2:** The on-axis effective area of the Athena telescope optics, as designed in the CDF [2], as function of X-ray energy, for three different SPO mirror module rib spacings. In the upcoming industrial system level phase A studies of Athena, the telescope mirror diameter and area will be optimised, and it will be investigated, whether a larger mirror effective area of 2 m<sup>2</sup> as proposed can be achieved respecting the cost and schedule constraints. All mirror modules are modelled as being coated with Iridium/ boron carbide bilayer. The figure includes a 10% loss due to contamination etc.

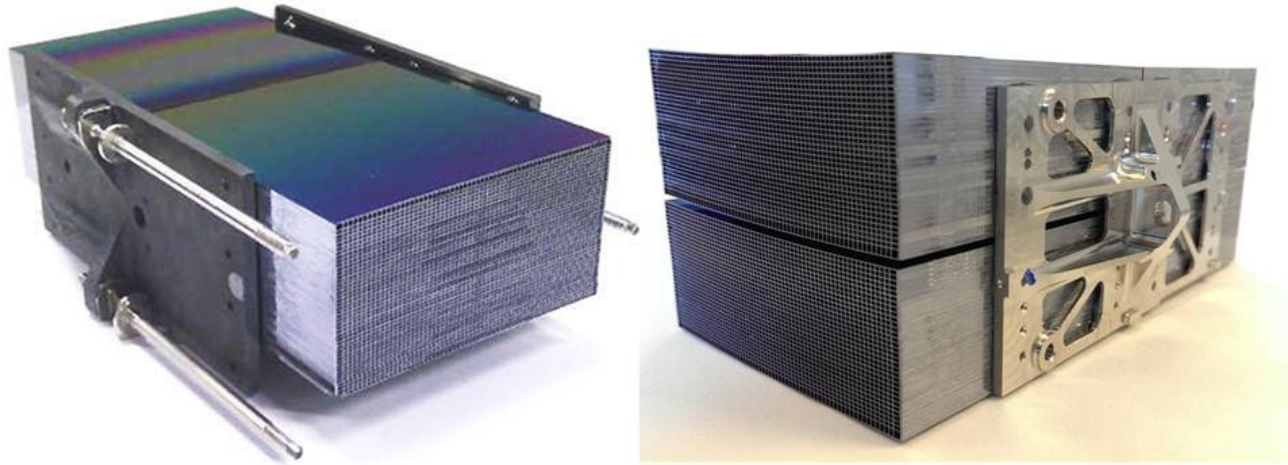
## 2. SILICON PORE OPTICS MIRROR MODULES – PRODUCTION AND TESTING

Building on semiconductor technologies developed for contemporary electronics, has allowed very cost effective development of the SPO, as an enabling technology for future science missions. Utilizing the superb quality of 300 mm Silicon wafers with their ultra-highly polished surfaces and excellent co-planarity, and largely employing existing tools and processes, X-ray mirror plates are produced, which are then robotically assembled into stacks, each containing up to 45 co-aligned mirror plates. The individual mirror plates are attached to each other by direct bonding, i.e. without any additional intermediate layers.

Four of such X-ray mirror stacks are then assembled into an SPO mirror module, with two precision brackets serving to maintain the alignment between the primary and the secondary reflector stacks, and at the same time to provide suitable interface elements to the optical bench structure. Dowel pins are used to isostatically mount the mirror module to the optical bench. The assembly of the mirror modules occurs at a synchrotron beam facility, providing X-ray metrology for the alignment.

Figure 3 shows such a mirror module on the left, using CeSiC brackets, optimising the match to the coefficient of thermal expansion of Silicon. On the right a mirror module with four mirror stacks is shown, effectively improving the

packing efficiency of mirror modules in the telescope aperture. Here invar is used as bracket material, improving the robustness of the optics.

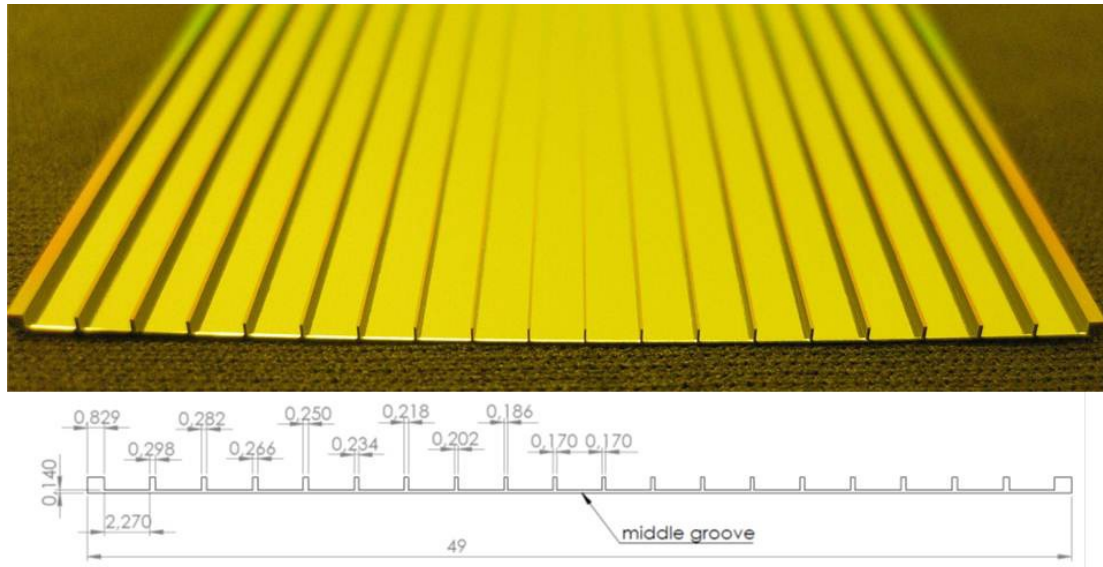


**Figure 3:** Evolution of the Silicon Pore Optics (SPO) mirror modules: Left single stack configuration (i.e. one primary and one secondary mirror stack in tandem) with CeSiC brackets, optimised for a wide operating temperature range. Right: double stack configuration (i.e. two primary mirror stacks above each other, followed by two secondary mirror stacks) with invar brackets, featuring a higher resistance to vibration and shock loads, and providing a larger packing efficiency.

The mirror plates in the primary stacks are tilted with respect to each other, by featuring a wedge on each bonding surface, achieving con-focality of the mirror plates. Also in the secondary stacks, the plates are progressively tilted, but the relative angle increment is three times larger, in order to achieve the Wolter geometry. In short we refer to this geometry as “ $1\delta / 3\delta$ ”, or “ $1/3$ ”. Alternatively the primary stack can have a divergent wedge, with an angle of  $-\delta$ , and the secondary stack a wedge of  $+\delta$ , which also produces a confocal optical system. This second approach, “ $-1\delta / +1\delta$ ”, has the advantage of requiring smaller wedges on the mirror plates and enabling a single mirror plate type to be used within a mirror module at a given radius.

From the start of the development, due attention was given to designing the production processes for SPO mirror plates and modules in order to prepare for cost effective mass production. Significant investments have been made to automatize all of the manufacturing steps, from the carving of the ribs, the etching of the wedges and the preparation of the mirror plates for bonding, to the stacking of the plates into mirror stacks.

Activities have started to produce mirror modules of the innermost radius of the Athena telescope, with a radius of only 250 mm. In figure 4 a mirror plate for such a module is shown, together with a drawing of its cross-section. The rib spacing has been increased from 0.831 mm to 2.27 mm, improving the effective area of the module (Note a 1 mm rib pitch is used in the mirror modules shown in figure 3). Additionally, the rib width has been made variable, allowing the optimisation of the bonding strength for each azimuthal position. The actual mirror membrane is only 140  $\mu\text{m}$  thick, reduced from the standard 170  $\mu\text{m}$  thickness, and the size of the mirror plate is 110 mm by 49 mm. The implementation of the associated mirror plate manufacturing equipment modification will permit also the production of optimised mirror plates for the other radii of the Athena telescope.



**Figure 4:** Inner mirror plate (radius 250 mm) with large rib spacing (2.27 mm) and thinner membranes (140  $\mu\text{m}$  thick mirrors). This mirror plate has been manufactured in preparation for the production of the first inner mirror module for Athena. The mirror plate production equipment was upgraded to maintain the good production yield despite the design evolution.

The innermost mirror modules are the longest, since they are closest to the optical axis of the telescope, and therefore the incoming X-rays are reflected at the smallest angles. The mirror modules on Athena are arranged in the Wolter-Schwarzschild configuration to improve the off-axis angular resolution, and their length shortens as  $1/r$ . The mirror module optical and mechanical design has to be accordingly optimised for each radial position, as indicated in figure 5.

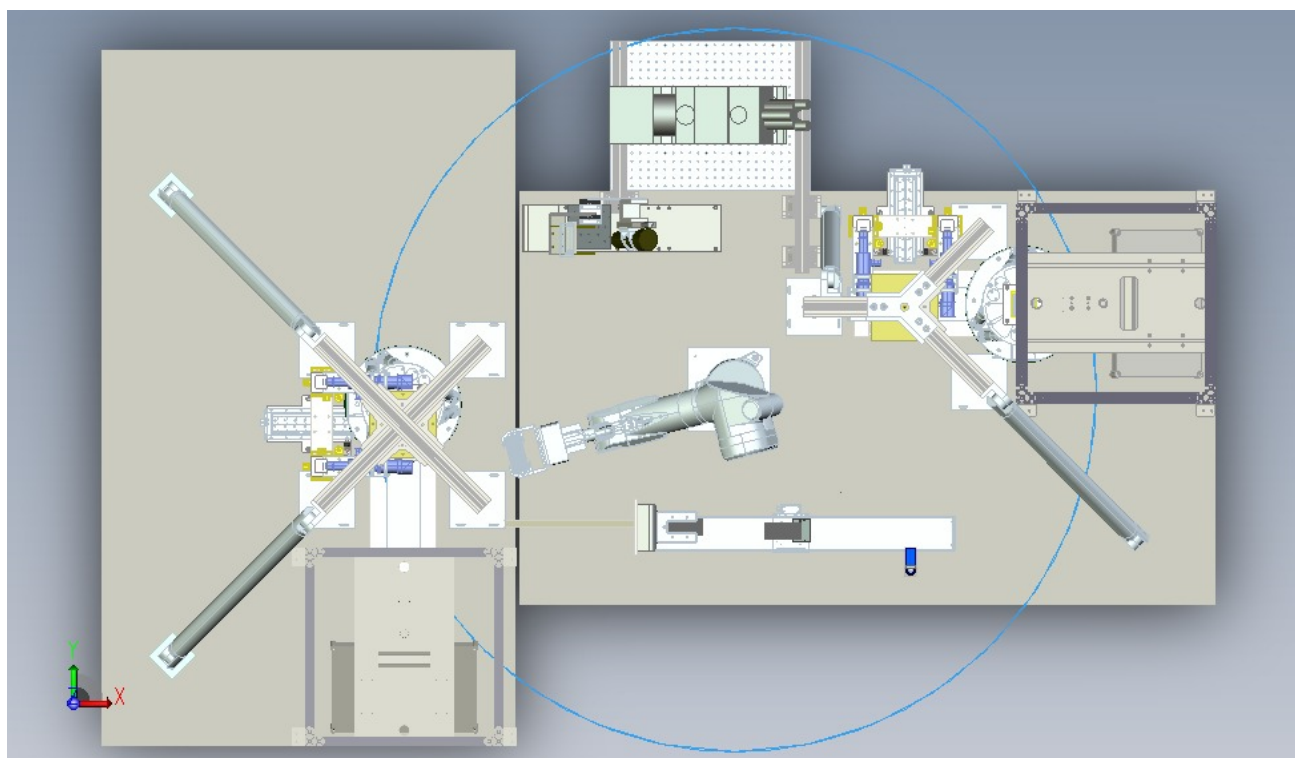


**Figure 5:** The mirror module geometry is dependent on the radial position in the telescope aperture. The inner modules (lower row numbers) are longer, since the incidence angles for the incoming X-rays are smaller. The length of the mirror



stacks in the modules varies between about 19.9 and 101 mm. Rows 16 to 20 have not been accommodated in the CDF study.

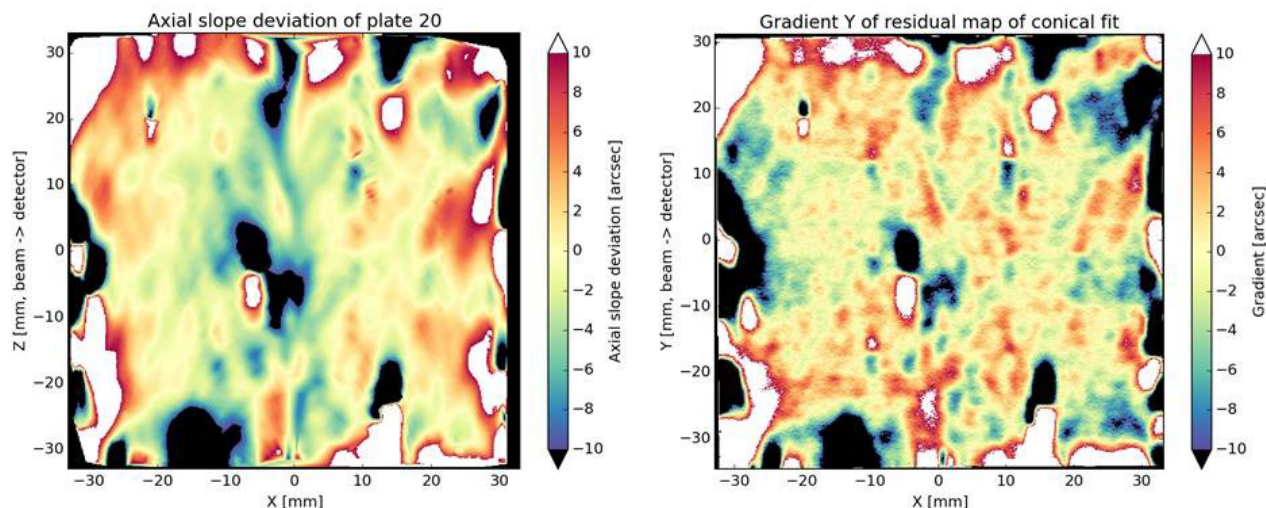
New equipment is also required for the stacking of the mirror plates for the inner modules. With the further evolution of the stacking robot used for the main SPO development (for modules with a radius of 747 mm), where each component of the machine, and each step of the process is re-assessed and improved, the SPO production equipment is improving the quality of the modules and the speed of production. The new stacking robot is placed in the same clean room as the current machine, and partly shares the ancillary equipment, e.g. the Nomarski inspection microscope, the feeding robot arm or the particle inspection equipment (see figure 6). The key components of the stacking robot are however independent: the stacking hexapod and mandrel, the plate shaping die, telecentric alignment cameras, or the surface figure metrology system (based on the Fringe Reflection Technique, FRT).



**Figure 6:** A new stacking robot (XOAT5) was designed and is being set up for stacking the mirror plates to produce the stacks for the inner mirror modules. The robotic arm is shared with the robot used to produce the medium radius mirror module stacks (shown on the left side), as are the particle inspection system and the microscope. The new robot has a dedicated surface figure metrology system and a modular stacking die to accommodate a large range of bending radii.

The online metrology system is essential for the automated remote stacking of the SPO mirror plates. The stacking operator is located in a control room, separated from the clean environment of the stacking robots. As in semiconductor fab-houses, provisions are made for grey area access to equipment for routine servicing.

The FRT metrology was inter-calibrated with pencil beam synchrotron radiation raster scans of the mounted mirror plates (see figure 7), showing a very good correlation.



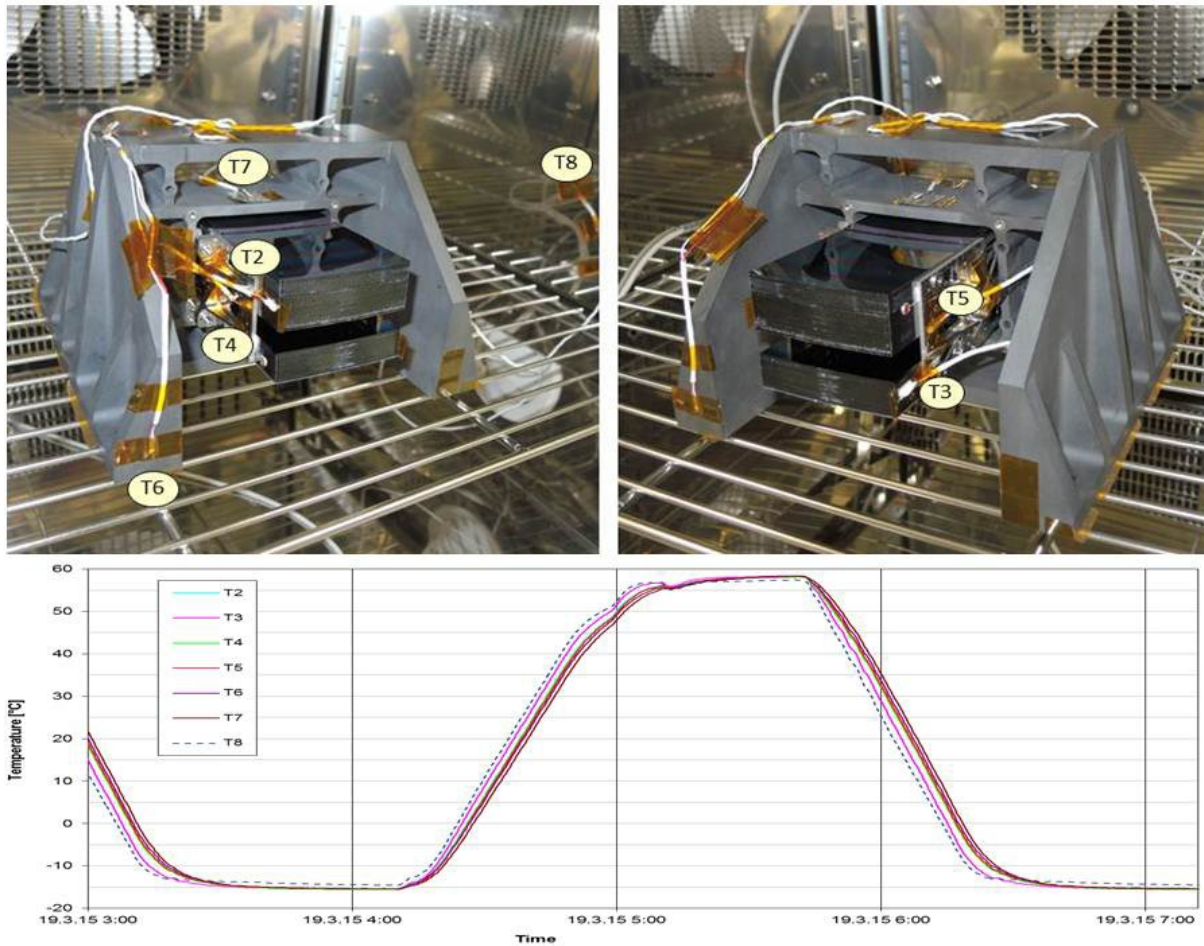
**Figure 7:** Comparison of two surface metrology systems used to characterise the stacked mirror plates: Left: high-resolution X-ray pencil beam scan of the top plate of the stack 675 at the Bessy II synchrotron radiation facility. A fine resolution scan was made at 2.8 keV, using a collimated beam of 50  $\mu\text{m}$  diameter. The measured slope errors (i.e. surface normal deviations from the nominal figure) are plotted. Right: the same stacked mirror plate as seen by the Fringe Reflection technique (FRT) system installed on the plate stacking robot. Again the surface slope deviations are plotted, using the same colour coding. The good correlation of the FRT surface metrology system available during the stacking operation and the X-ray metrology facilitates the production of high quality mirror stacks.

Progress has also been made with the thermal testing of SPO mirror modules. Simulating the expected lifetime of Athena, 60 thermal cycles from  $-15\text{ }^{\circ}\text{C}$  to  $+55\text{ }^{\circ}\text{C}$  were applied to the mirror module in a thermal chamber purged with gaseous Nitrogen (figure 8). During heating and cooling the temperature slope was about  $2\text{ }^{\circ}\text{C}$  per minute. Thermal sensors were mounted on several location to monitor the temperatures. Pictures of the test set-up were taken at the beginning and after several cycles, whenever the chamber temperature was at ambient temperature during working hours. No deviation or failure was observed.

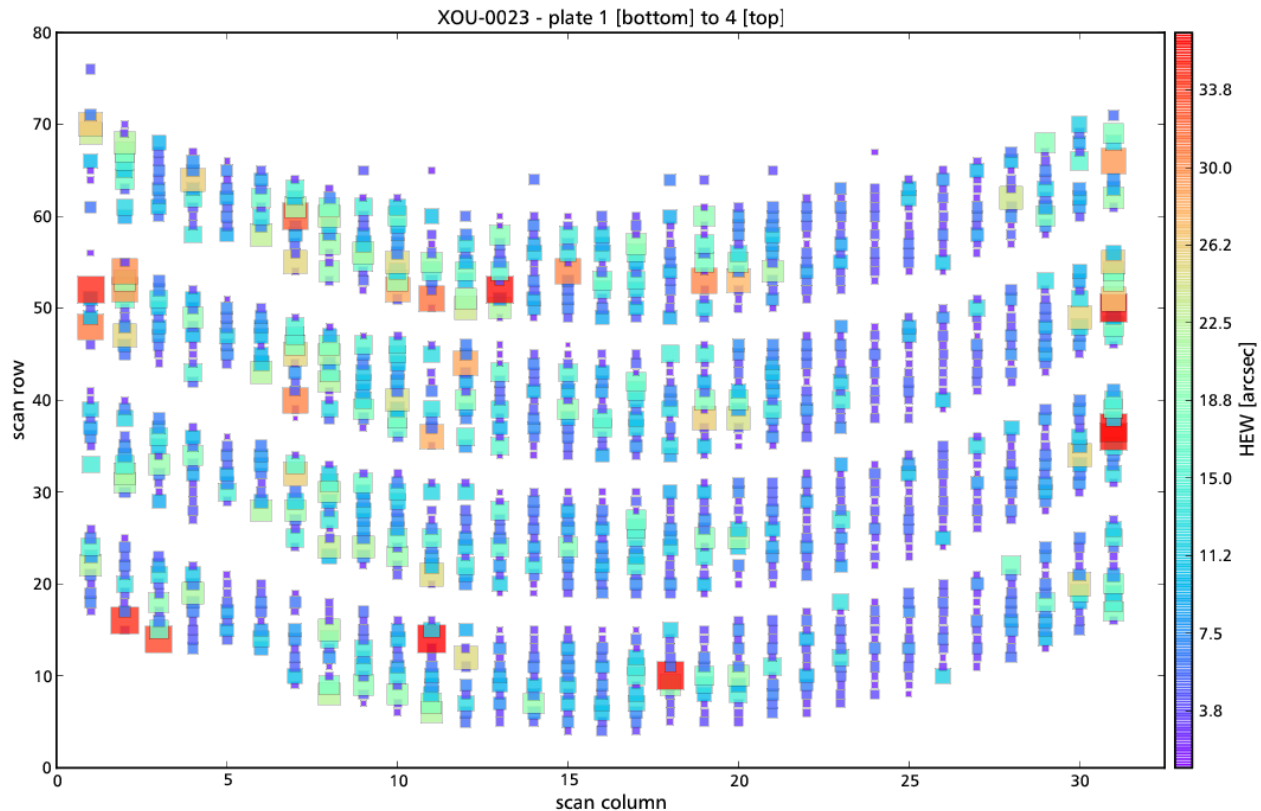
The optical quality of the mirror modules produced is measured with X-ray illumination. Recent results show a HEW of 11.2" (measured at Bessy-2 at the 5 meter station, and projected to the focal plane at 20 meters – note the current stacking robot is designed for the IXO requirements) for 81% of the measured surface, amounting to about 75% of the complete mirror module surface.

In figure 9 the local imaging properties of the first four mirror plate pairs of a mirror module are presented. The imaging quality is expressed as HEW in arc-seconds, and is represented by the size and colour of the squares plotted.





**Figure 8:** Thermal cycling tests of the SPO mirror module were performed, where 60 thermal cycles were applied. The mirror module was mounted in a representative structure using the isostatic mounting system developed for this optics technology. The location of the thermal sensors is indicated in the photographs. Detailed inspections before and after the thermal tests did not evidence any changes.

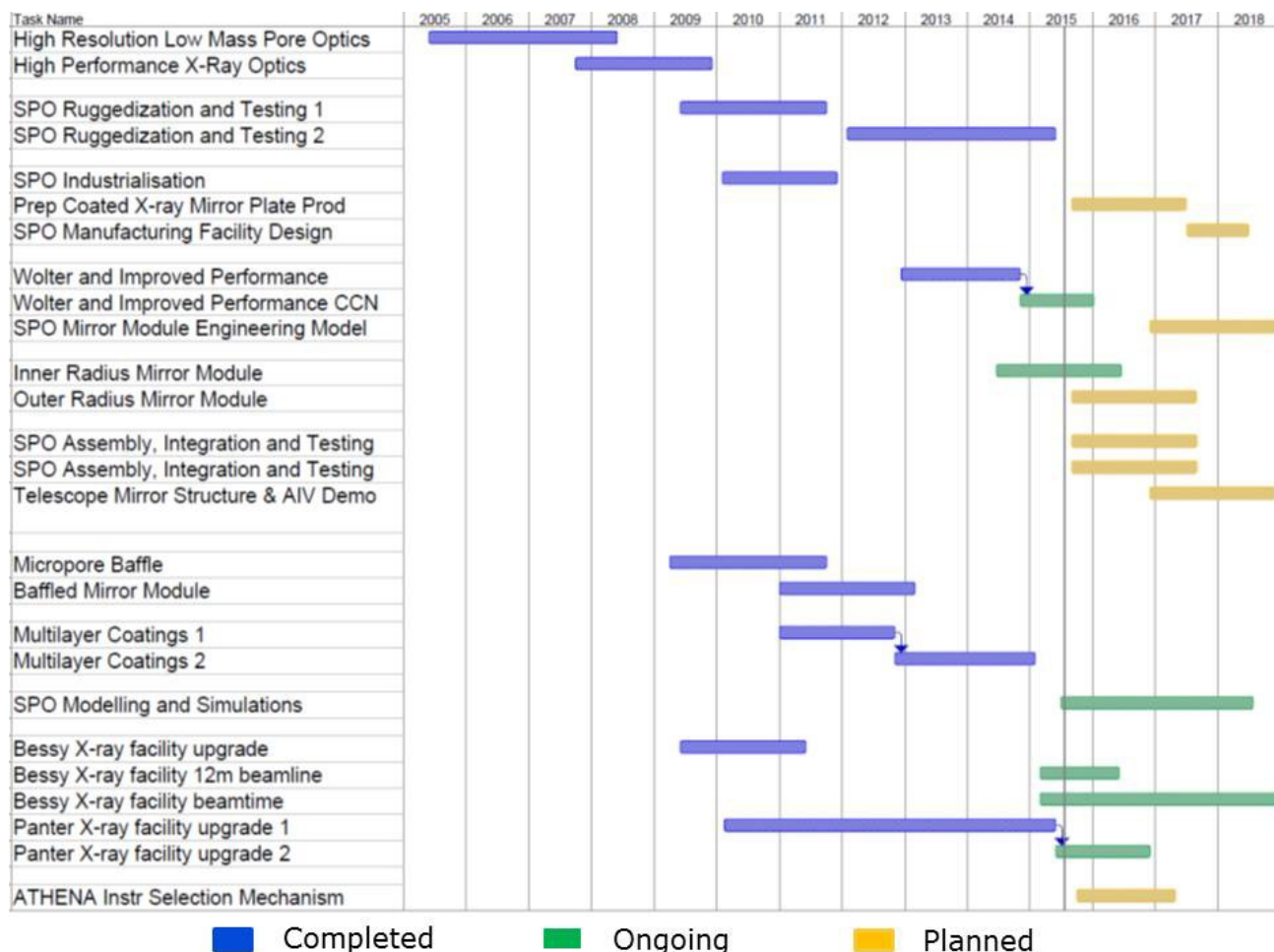


**Figure 9:** X-ray imaging performance of an SPO mirror module measured by pencil beam scanning at the Bessy-II facility. A map of the mirror stack aperture is shown, covering the full width of 4 mirror plate pairs. The local properties of the mirror are displayed with small squares, the color and size of which represent the local measured HEW. In this sample the right-hand third of the mirror (except the very edge) shows a good performance with HEW values ranging from 4 to 8 arc seconds.

### 3. TECHNOLOGY AND INFRASTRUCTURE DEVELOPMENTS

Following the selection of Athena as the L2 ESA Science mission, the associated technology plan has been updated (see figure 10). A further update is currently in preparation, taking consideration of the progress in the system definition of Athena and the on-going technology activities.

The technology design principle continues building on the automated production, preparing the industrialisation required for the later implementation phase of the mission.



**Figure 10:** A technology development plan for the preparation of the Silicon Pore Optics technology for Athena has been elaborated. This plan is being annually updated and expanded. Activities regarding the industrial coated plate production, the outer mirror module development, and the mirror selection mechanism have recently been added, and further activities are being defined for the November 2015 update of the plan (not shown in this figure).

The main SPO Development Activities remain focused in five areas:

1. Ruggedisation of Silicon Pore Optics
  - Closing activity SPORT-2: conservative environmental assumptions
  - Re-designed mirror brackets (now Invar), glue pads, pins etc.
  - Vibration, shock and thermal tests
  - Planned activity: SPO MM Engineering Model
2. Improved Angular Resolution SPO mirror module
  - Running activity WOLTER (CCN) aiming at 5" (Athena-L2,  $f = 12$  m)
  - Introducing secondary curvature (had conical approximation before)
  - All steps of SPO MM production addressed
3. Demonstration of Inner/Outer Radius mirror module with  $f=12$  m
  - Started new development activity on Inner mirror module: SPIRIT
  - New stacking machine and tools for  $f=12$  m,  $r \sim 0.25$  m
  - Outer mirror module: ITT issued; steps: 10" at  $f = 20$  m  $\rightarrow$  10" at 12 m  $\rightarrow$  5" at 12 m

4. Industrialisation Aspects
  - Concluded SPO Industrialisation TDA: SPIN
  - Issued ITT for coated mirror plate production
  - Planned activity on SPO mirror module engineering model
  - Planned activity on SPO manufacturing facility design
5. Accommodation and System Aspects
  - Concluded SPO end-to-end TDA: HPO
  - Placing activity on SPO mirror module AIT
  - Issued ITT for Instrument Selection Mechanism
  - Issued ITT for activity on telescope structure and optics integration

Facilities are also required to be developed in parallel, and two independent facilities are being utilised: pencil beam scanning is used in the laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the BESSY II synchrotron radiation facility in Berlin, and at the complementary Panter facility full beam illumination measurements are conducted (operated by the Max –Planck Institute for Extra-terrestrial Physics, MPE) [33-35]. Both facilities are being upgraded (see figure 11).

A dedicated beamline for the characterization of the ATHENA silicon pore optics is currently being installed in the laboratory of the PTB at BESSY II, where also the existing pencil beam facility XPBF is located. At the new beamline XPBF 2.0, a monochromatic parallel beam with a photon energy of 1.6 keV will be produced using a multilayer-coated toroidal mirror, deflecting the beam in the horizontal plane by 17°. With apertures and pinholes, different beam sizes and shapes from about 50  $\mu\text{m}$  diameter up to about 5 mm x 5 mm can be realized while the beam divergence should remain below 2 arc second (1 arc sec for the small beam). A hexapod system will be used in vacuum to align the optics to be investigated in all degrees of freedom with below 1 arc second precision. A CCD-based detector system will be used to register the direct and the reflected beam at a distance of 12 m from the optics, thus at the currently foreseen focal length of ATHENA. In order to follow the reflected beam, a vertical translation system of the camera with a travel of 2 m will be installed, which will also maintain the vacuum connection between the detector and the sample chamber.



**Figure 11:** Suitable test facilities are being prepared for the further development of the SPO mirror technology. Left: a new beamline is being installed in the PTB laboratory at BESSY II in Berlin. It will provide a collimated 1.6 keV pencil

beam with a size of 50  $\mu\text{m}$  to 5 mm, a precision hexapod positioning station with autocollimator feedback metrology, and a focal plane detector for testing 12 m focal length optics. Right: Accommodation studies have been initiated, to investigate the end-to-end testing of the complete Athena mirror at the Panter facility near Munich. This involves the study of the required infrastructure including cleanrooms, airlocks, manipulators and buildings. The Panter facility allows large area illumination with X-rays of different energies, with a source located at 130 m distance.

## 4. CONCLUSION

With the selection of the Athena mission as the second large class ESA science mission the development of the SPO technology is being ramped up. Complementing the system level studies, the Athena optics technology development continues to follow the established and proven track, focusing on the angular resolution, the environmental compatibility and industrialisation for the middle, inner and outer mirror modules. In particular the spacecraft accommodation aspects (mirror optical bench structure, hexapod mechanism, mirror module assembly, integration and test) are gaining importance, and the required X-ray test facilities are being prepared.

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